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FATIGUE TESTING TECHNIQUES FOR EVALUATING THE EFFECTS OF ENVIRONMENT ON COMPOSITE MATERIALS

Michael D. Hanson

Army Air Mobility Research and Development Laboratory
Fort Eustis, Virginia

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Preliminary flexural tests were conducted on ±45° fiberglass-epoxy and on graphite-epoxy cantilever bending specimens to determine fatigue life. Resonant testing (constant stress) was abandoned because of difficulties in keeping the specimens tuned to their resonant frequency. A constant-deflection technique proved to be satisfactory. A peak-to-peak amplitude of 3.25 cm (corresponding to an outer fiber stress level of 22 ksi) was found to give a fatigue life of about 2×10^6 cycles. Long-term indoor/outdoor tests will be conducted to determine the environmental effects on the fatigue life of the composites. The specimens will be cycled daily such that the projected fatigue life without degradation will be 2 years.		

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INTRODUCTION

Composite materials are finding an increasing usefulness in aircraft structures. Most of the materials data used in the design of aircraft are obtained under generally mild or controlled environmental conditions (i.e., temperature, humidity, etc.). However, aircraft structures are subject to long-term, uncontrolled weathering conditions.

In order to obtain data that are representative of actual operating conditions, cantilever bending fatigue testing of ±45° fiberglass specimens and graphite composite specimens was initiated on outdoor and indoor test equipment. Initially, the specimens were tested using a resonant technique that had proven to be successful with similarly designed metal specimens. However, difficulties in maintaining the specimens at their natural frequencies were encountered. The resonant frequency would shift slightly after a few thousand cycles, putting the system out of tune.

After trying several unsuccessful modifications to the test procedure, it became obvious that state-of-the-art, metal testing techniques did not yield valid data. It was decided to abandon the free-vibration approach. An indoor shaker table was modified to produce a fixed deflection on the specimen with a system of actuator arms. Tests were run to determine the fatigue life at different magnitudes of deflection using this system, and they proved to be successful.

The techniques developed in this pilot program will be used in a major program to obtain long-term fatigue data.

FABRICATION AND PREPARATION FOR TEST

One hundred thirty 12-ply fiberglass specimens and ninety 12-ply graphite specimens were fabricated using a ±45° layup scheme.

The fiberglass specimens were made of 1002-S prepreg unidirectional tape. The fiberglass was cured at 325°F and 25 psi for 30 minutes, followed by a 16-hour postcure at 280°F.

The graphite specimens were made of Modulite 5206 - Type II prepreg unidirectional tape. They were cured at 275°F and 100 psi for I hour. The temperature was elevated to 350°F for 2 hours, followed by a postcure of 400°F for 2 hours.

The coupons were shaped to have the maximum stress near the middle of the beam. The dashed lines in Figure 1 represent a constant stress planform in the cantilevered beam. The maximum stress[1] occurs at the point where the arcs of a circle (represented by the curved sides of the specimen) become tangent to the dashed lines.

In addition to the fiberglass and graphite specimens described above, some promising specimens were obtained from Kaman Aerospace Corporation (Figure 2). They were unidirectional sandwich samples and were designed to have a stress concentration at the apex of the triangular-shaped sandwich core material (arrow in Figure 2). In preliminary tests, these specimens failed, predictably, in the outer fibers near the tip of the sandwich core area (Figure 3). Although satisfactory, these specimens were not used in subsequent tests because of the difficulty of specimen fabrication and the unknowns relative to the magnitude of the stress configuration.

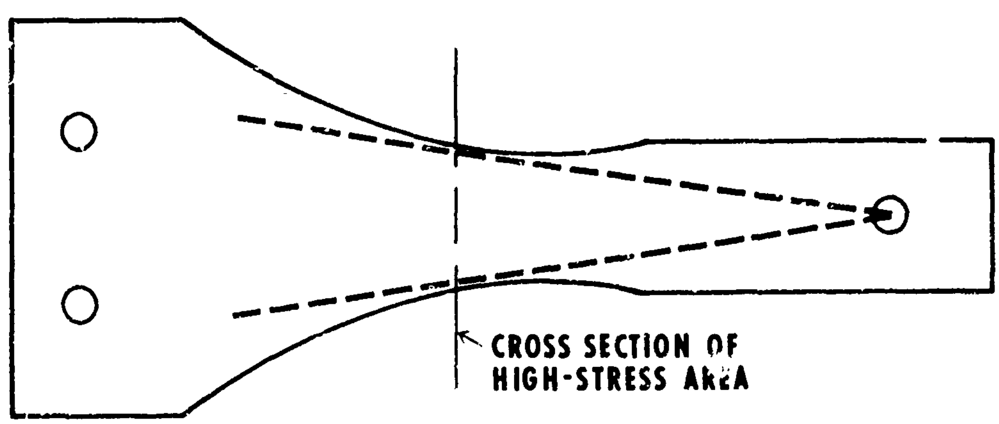

Figure 1. Specimen configuration.

[1] H. Leybold, H. Hardrath, and R. Moore, *An Investigation of the Effects of Atmospheric Corrosion on the Fatigue Life of Aluminum Alloys*, NACA TN 4331, Langley Field, Virginia, 1958.

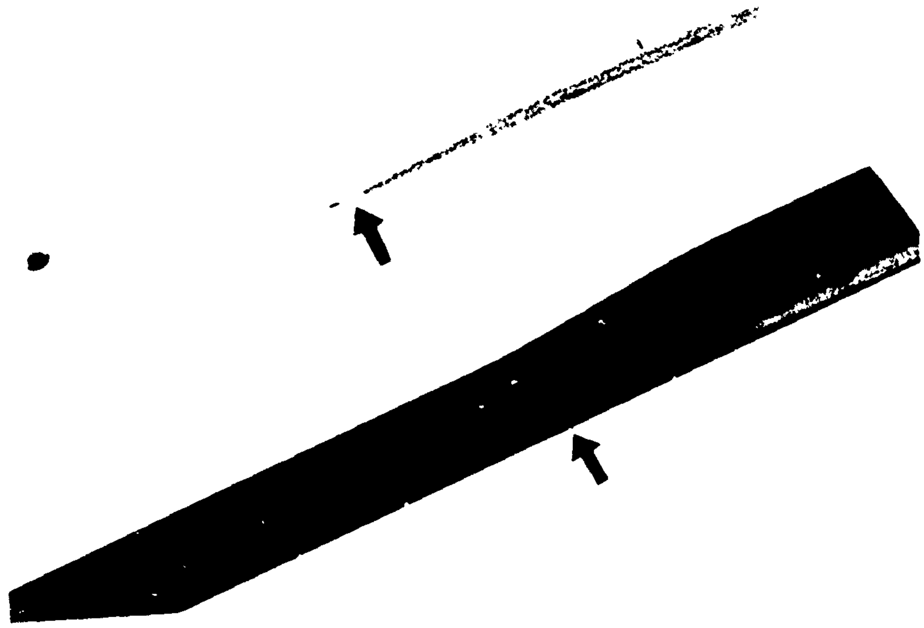

Figure 2. Kaman sandwich specimens.

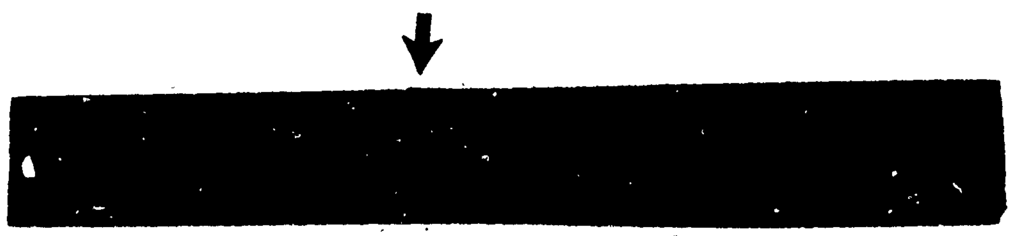

Figure 3. Failure of Kaman specimen.

TEST EQUIPMENT AND PROCEDURES

Specimens were fatigued in cantilever bending on a vertical shaker table indoors to deter mine fatigue life.

The initial group of specimens was allowed to vibrate freely with weights on the tip of each specimen. The tip weights were adjustable to allow the resonant frequency of each specimen to be tuned to the frequency of the table (Figure 4).

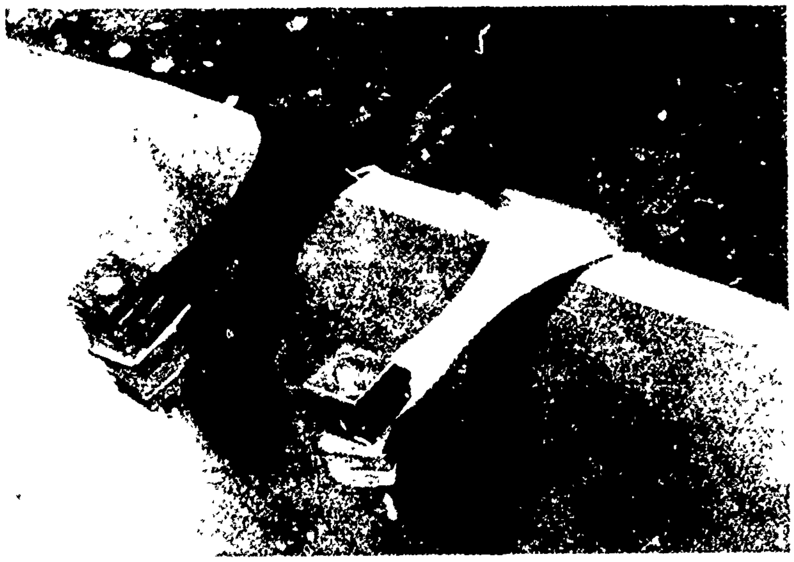

Figure 4. Resonant test configuration.

The setup for the second group was similar to the first except that the tip weights were supplemented with additional weights suspended on soft springs to apply a mean load (Figure 5). The spring-supported weight was suspended in an oil bath. The combination of the soft spring and the oil (damper action) decoupled the mean load (weights) from the dynamic loading.

The third group, consisting of five graphite specimens, was loaded in a forced-vibration system. Actuator arms transmitted motion from the table through a lever system to the tips of the specimens, thus producing a fixed-amplitude deflection (Figure 6). The fixture for the third group was adjusted to allow the specimens to flex in one direction only. Therefore, the uppermost fibers, as the specimens were mounted in the machine, were fatigued in tension and the lowermost fibers in compression.

Static-deflection tests, used to determine failure, were performed at regular intervals with weights of 0, 500, 1000, and 2000 grams. Static-deflection measurements were made after 10, 100, 1000, 10,000, and 100,000 cycles and thereafter at every 100,000 cycles.

Also, at regular intervals, the maximum stress encountered during the fatigue cycle was determined statically by adding weights to the tip until the deflection was equal to that produced by the machine. The moment and stress were calculated from these data using elastic beam theory.

Figure 5. Resonant test configuration with decoupling springs.

Figure 6. Constant deflection test configuration.

TEST RESULTS

The tests with the initial and second groups of specimens, in the free-vibration configuration, proved to be unsatisfactory. The specimens would not remain tuned for any significant length of time.

With the third group of specimens, in the forced-deflection, fixed-amplitude configuration, valid data were obtained. Specimen 1 was cycled with a fixed deflection of 2.5 cm. Specimens 2, 3, and 4 had a fixed deflection of 3.25 cm, and specimen 5 underwent a deflection of 2.75 cm. Specimen 1 did not fail after 6 x 10^7 cycles, and specimen 5 did not fail after 2 x 10^7 cycles. However, the stress level decreased from 16 ksi to 10 ksi in specimen 1 and from 19 ksi to 12 ksi in specimen 5 due to creep.

Specimens 2, 3, and 4 all failed at about 1.7 x 10^6 cycles. A plot of deflection versus cycles for specimens 1 and 2 is presented in Figure 7. The curves for specimens 3 and 4 essentially fell on the curve for specimen 2, and the curve for specimen 5 essentially fell on the curve for specimen 1. In those specimens that failed, small cracks appeared in the tension surfaces at between 50,000 and 500,000 cycles. Complete separation of the upper lamina occurred between 500,000 and 1.5 x 10^6 cycles (Figure 8). Little difference was noted among specimens 2, 3, and 4 in the static-deflection tests despite the wide range in cycles-to-delamination among the specimens. The lowermost lamina (compression surface) was completely separated by 1.5 x 10^6 cycles in these three specimens. Some delamination was noted in the layer next to the uppermost lamina in one specimen after the uppermost layer had separated. None of the specimens failed catastrophically, but they were removed from the test fixture when static tests indicated a sudden change in the deflection (under fixed load) versus cycles curve.

Table 1 summarizes the test results.

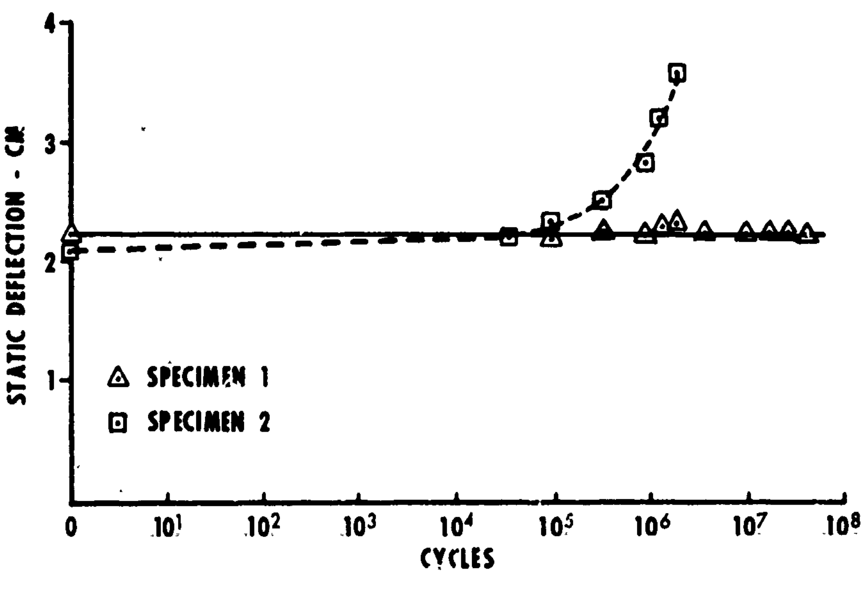

Figure 7. Static deflection versus cycles.

Figure 8. Delamination of graphite specimen.

TABLE 1. STATIC DEFLECTIONS OF FATIGUED SPECIMENS (CM)

Cycles	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5
0	2.16	2.07	2.00	2.07	2.22
50×10^3	2.24	2.25	*	*	*
100×10^3	2.24	2.28	2.18	2.25	2.33
500×10^3	2.23	2.53	2.44	2.41	2.38
1×10^6	2.26	2.80	2.67	2.62	2.40
1.5×10^6	2.28	3.25		2.96	2.42
2.0×10^6	2.32	3.53	3.17	3.97	2.50
5.0×10^6	2.31	Failed 1.5×10^6		Failed 1.7×10^6	2.47
10×10^6	2.31				2.45
20×10^6	2.39				2.49
30×10^6	2.36				Runout
60×10^6	2.33				
	Runout				

* No data taken

DISCUSSION

Although only five specimens were tested, these five showed that the extreme laminae in a multilayered structure essentially fail before delamination and cracking occur. For example, the uppermost layer of specimen 3 was delaminated after 50,000 cycles. The same layer on specimen 4 was completely intact (by visual inspection) up to 1,300,000 cycles. Yet, at 100,000 cycles when static-deflection tests were made, the static deflection in each specimen had increased .18 cm from that at 0 cycles. In fact, specimen 4 failed earlier than specimen 3 (1.7 million cycles compared to 2 million). For this reason, observable damage was not used as a criterion for failure.

When delamination did occur and cracks appeared, all cracks were parallel to the lay of the fibers. It appeared that the failure was in the resin matrix. Fiber damage was not evident under a 20-power microscope.

Failure was determined when the deflection versus cycles curve made a radical departure from a smooth curve. For specimens 2, 3, and 4 this occurred between 1.5 and 2 million cycles. The static tip deflection at failure was about 3.15 cm with a load of 2 kg.

As mentioned before, the calculated stress level based on the original cross-sectional area decreased with an increase in fatigue cycles. In actuality, the loads producing the deflection decreased. However, based on actual effective area, the stress increased (due to the failure of several laminae). Relating these facts to an operational aircraft, it is felt that the deflection capacity of a structure is more indicative of failure than is the stress. Difficulty in the determination of ineffective laminae is a primary consideration. In addition, stresses were computed using elastic beam theory, which may not be valid for the specimens tested. Therefore, the stresses expressed should be taken as relative measures of structural integrity of the entire structure tested and not as the actual stress occurring in the load-carrying fibers.

Table 2 summarizes calculated stresses, and Figure 9 is an S-N curve of the fatigued specimens.

TABLE 2. CALCULATED STRESS LEVELS

	Specimen 1	Specimens 2, 3, 4	Specimen 5
Cyclic deflection (cm)	2.50	3.25	2.75
Stress (ksi) after			
0 cycles	15	23	19
1×10^6 cycles	*	17	16
2×10^6 cycles	*	12	15
3×10^6 cycles	*		14
10×10^6 cycles	14		12
20×10^6 cycles	14		12
30×10^6 cycles	12		
60×10^6 cycles	10		

* No data taken

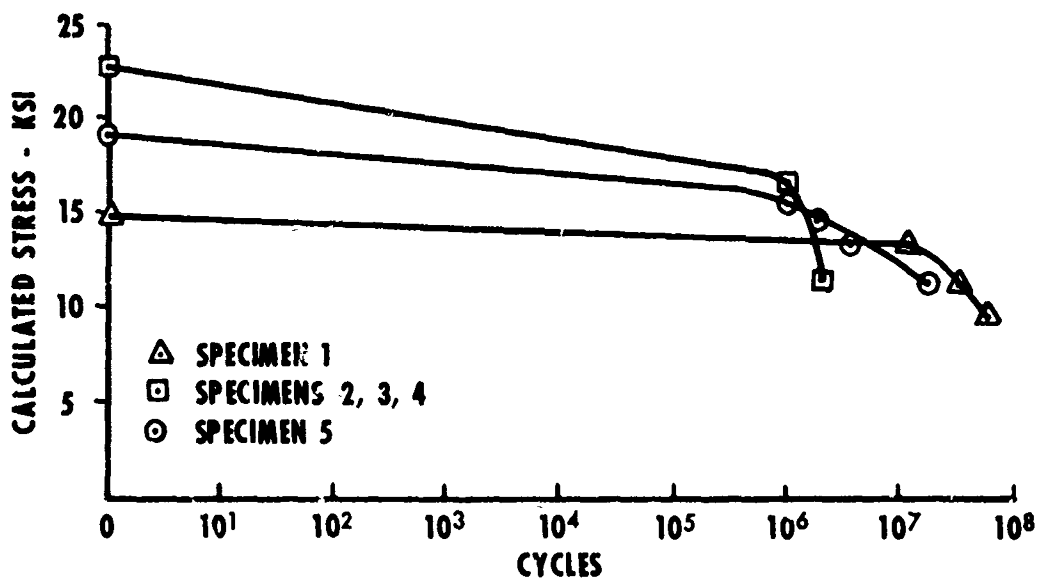

Figure 9. Calculated stress versus cycles.

CONCLUDING REMARKS

Fatigue failure of composite materials is difficult to assess. Visual evidence of delamination is not particularly helpful since the degradation of material properties appears to be more of a factor in failure than the delamination. Therefore, a sudden change in the static deflection versus cycles curve was the criterion for failure.

Resonant testing of composite bending specimens is inadequate for fatigue life determinations. The material properties of the composite change gradually, and the resonant frequency of the specimen changes coincidentally. The time required to periodically retune each specimen precludes the long-term testing of composites in this manner.

Fixed-deflection techniques were developed to fatigue test composite bending specimens. Actuator arms transfer motion from a shaker table to the tips of the specimens. The specimens then undergo a constant fixed deflection.

The effects of a weathering environment on the fatigue behavior of composite materials will be determined in a follow-on program over a 2-year period using both glass and graphite specimens. It will aid the designer of future structures, especially of aircraft structures, where light weight and corrosion resistance are necessary.

CONTINUING PROGRAM

The planned program to obtain long-term fatigue data will use equipment that has been modified to produce a fixed deflection in the specimens. All specimens will be fatigued on a single machine. Specimens will be subjected to the environment and will be brought in on a weekly basis for 20,000 cycles such that the cumulative cycles result in the projected fatigue life of 2 years (based on indoor behavior).

Half of the specimens will contain a 1/4-inch-diameter hole in the area of highest stress. Some of the specimens will have a gel coat of the matrix epoxy to determine if the coating will provide protection from the environment. Other specimens will be coated with paint that is opaque to ultraviolet (UV) radiation to determine the effect of UV light on the composites.

Three specimens of each composite will be subjected to high humidity and high temperature (120°F) in an environmental chamber. Other samples will be subjected to a low-temperature environment (0°F), and another group of specimens will be subjected to a high ultraviolet environment using UV lamps. All of these specimens will be cycled with the other specimens to determine the effects of extreme conditions on the fatigue life of the composites.

Before testing and after the specimens have failed, an infrared scan of the matrix material will be made. Tensile tests will be conducted using coupons cut from the untested panels and from fatigue specimens.